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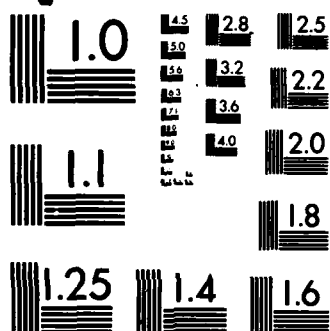
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LINEAR ACTUATOR FOR LARGE SPACE STRUCTURE

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DAYTON, OHIO 45424

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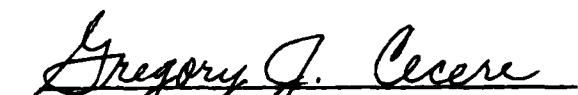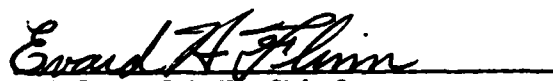WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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The impending use of large structures in space has created a requirement controlling their alignment. Structures used for energy gathering, such as antennas or solar energy concentrators, must maintain accurate mechanical alignment in order to operate at maximum efficiency.

This paper describes a linear actuation approach designed to meet the alignment requirements of space structures. The approach is based upon using a fluid pump to expand and contract two chambers enclosed by metal bellows. The general configuration is valid for a wide range of force, rate and stroke requirements required for different structure designs.

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FOREWORD

The effort described in this document was performed by Dynamic Controls, Inc. of Dayton, Ohio under Air Force Contract F33615-83-C-3601. The work under the contract was carried out in the Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio. The work was administered by Mr. Gregory Cecere, AFWAL/FIGL Program Manager.

The authors wish to express their appreciation to Mr. Morris Ostgaard, Research and Technology Assistant for the Flight Control Division, AFWAL/FIG, for his posing the problem to which the investigation was directed. Appreciation is also expressed to Dynamic Controls, Incorporated employees Linda Clere for preparation of text and illustrations used in the report, and Connie Graham for design and fabrication of the control electronics used to power the space actuator.

This report covers work performed between March 1983 and May 1984. The technical report was submitted by the authors in September 1985.

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SECTION I. INTRODUCTION

The ability to construct large structures in space has been made practical by the success of the space shuttle program. Materials for the large structures can now be transported to an appropriate orbit and assembled. Structures 300 meters or more across are considered feasible. The structures will be low mass and flexible. Controlling the mechanical alignment of such structures, for example --- large antennas, is critical to their operation. Figure 1 is an artist's illustration of such a structure deployed in orbit around the earth. Note that the structure illustrated is a truss construction with rigid links connected in triangular patterns.

Alignment of a structure can be accomplished by inserting linear actuators in selected positions within the structure. The actuators are commanded to extend or retract in order to maintain the structure in a desired shape. There is no requirement for position feedback around each actuator. However, the actuators should hold their existing length unless commanded to extend or retract.

The space environment is characterized by high vacuum, particle and electromagnetic radiation, meteroids and zero gravity. Solar energy can cause widely varying temperatures. The requirements for an actuator to align a space structure are unique to the space environment and include the following:

   a. The actuator must operate in a vacuum

   b. The actuator is subjected to operating temperatures varying from -100° to 300° F.

   c. The dynamic response requirements for the actuator are low (flat frequency response to 1 Hz or less).

   d. The actuator must operate with little or no maintanence for extended periods of time.

   e. The force requirements are low, being primarily the force to overcome friction.

Rotary actuators produce a continuous torque in one direction in order to provide a continuous output motion. This torque must be balanced inside the actuator to prevent it from affecting the rest of the system.

One linear actuation approach that meets the preceding requirements and avoids the torque problem is a design using a fluid pump to expand and contract two chambers enclosed by metal bellows. Increasing the volume of fluid in one chamber by pumping from the other causes the actuator to extend. Reversing the pumping direction causes the actuator to retract. The actuator is a closed system with no sliding seals. Silicone oil is used as the fluid for the actuator because of its viscosity change with temperature characteristic and its high flash temperature (greater than 500°F).
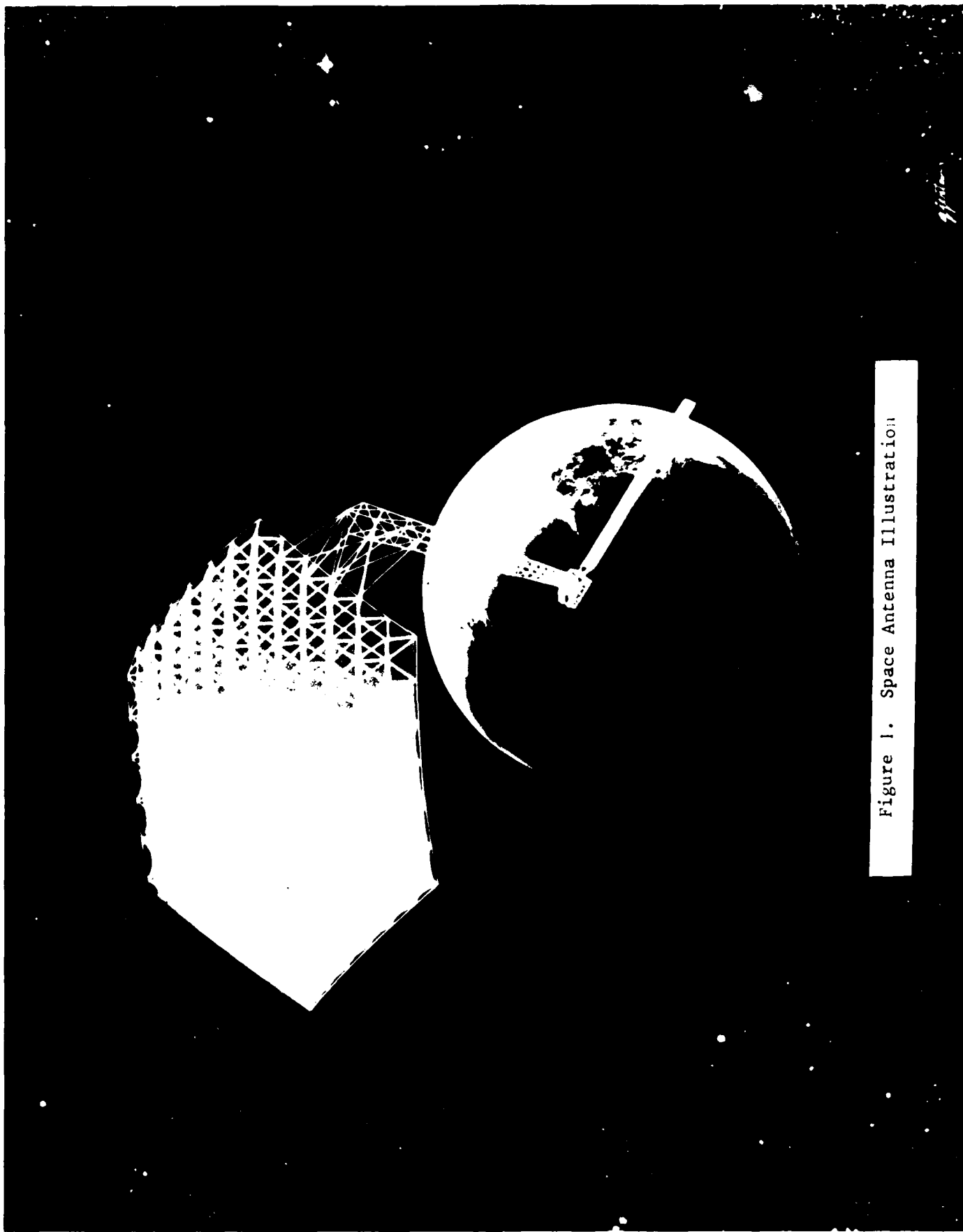
Figure 1. Space Antenna Illustration

SECTION II. MECHANIZATION DESCRIPTION

1. General

The problems of fluid component design generally associated with operation under high vacuum conditions are sublimation and evaporation of materials, cold welding, friction and wear. One of the problems associated with sublimation is that the sublimated materials tend to plate out on cooler surfaces. This plating could have a negative effect on the operation of other components. Metals sublimate at increasing rates directly with increasing vapor pressure. Aluminum, for example, sublimates at about 3.94×10^{-6} in./year at a temperature of 1020 °F. Iron sublimates at the same rate at 1420 °F. The operating design temperature for the alignment actuator is 300 °F which is considerably lower than the preceding temperatures at which metal sublimation could be a problem. Polymers, such as Teflon, do not evaporate or vaporize in vacuum. At elevated temperatures, they do decompose. However, for Teflon, the elevated temperature at which a 10%/year weight loss occurs is 710 °F. Again this is considerably above the expected temperature at which the space actuator will be subject. Pure metals sublimate faster than alloys and oxide coatings can reduce sublimation rates. This actuator is designed to incorporate an oxide coated aluminum cover which should minimize the sublimation problem. The stainless steel bellows cannot be coated because they must flex. The material which sublimates from the bellows should be contained by the actuator cover and plate out inside the actuator. However this plating will not sublimate enough to affect the actuator's operation even after several years. The containment cover will prevent the actuator's sublimation from having more than a minimal impact on other components in the structure. The elastomer seals sublimate faster than metal. Silicone elastomers undergo a 10% weight loss per year at a temperature of 400 °F, 100 °F above the design temperature for the actuator. However, sublimation rate is a function of surface area exposed to the vacuum and the seals will have only a thin line exposed to the vacuum. The material loss is expected to be low enough to allow the seals to last for several years.

2. Specific

The materials used in the construction of the actuator are:

    a. Aluminum
    b. Stainless Steel
    c. Teflon
    d. Flurosilicone Elastomers
    e. Copper
    f. Samarium Cobalt

The main structure of the actuator is fabricated from aluminum. Stainless steel is used for the bellows, fasteners, force motor frames and springs. Teflon is used as a bearing material, both in rollers and sliding shaft guides. Flurosilicone elastomer is used for the "O" ring seals. The force motors used in the fluid pump use stainless steel in the housings, copper wire in the driving coils and incorporate Samarium Cobalt magnets. If necessary for long

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term operation, metal seals can be substituted for the flurosilicone static seals used between the sections of the actuator in order to minimize sublimation of the static seals. Figure 2 is a photograph of the actuator constructed to demonstrate the concept. As shown on Figure 2, the entire center section of the actuator within the three rails moves relative to the rails. The position bellows at the right end of the center section is used to drive the center section. Two of the three coil springs used to establish a quiescent pressure above ambient pressure can be seen in Figure 2.

Hydraulic systems in space have the risk of being pierced by meteroids. If the fluid escapes, it may spread over a large area and condense out on lenses and electrical connections. The aluminum cover should provide sufficient protection from meteroids of the size that are expected to be encountered.

The actuator was designed so that the entire center section moves relative to the outer frame. This allows the two masses of the actuator which move relative to each other to be about equal. This maintains the actuators center of gravity in the same relative position to the ends (i.e., if the center of gravity was at the center at full retract, it would remain at center at full extend). The actuator could easily be modified to allow the center of gravity to remain a fixed distance from one end.

Figure 3 is a schematic of the fluid transfer circuit for the actuator. The circuit uses four spring loaded ball check valves, two floating checks, two pump bellows, a reservoir bellows, a position bellows and two electromagnetic force motors. Fluid is transferred between the reservoir and position bellows by the check valve pumps. The direction of fluid transfer is determined by which pump (extend or retract) is operated. The floating checks prevent backflow through the pumps when there are different pressures in the reservoir and position bellows.

Figure 4 is a pictorial of the fluid transfer circuit element arrangement as used in the actuator. The check valves and floating checks are mounted in a cylindrical housing with the position bellows attached to one face of the housing and the two force motors and bellows attached to the opposite face. The reservoir bellows is attached to the housing supporting the force motors which drive the pump bellows.

The actuator will move a fixed amount for a given stroke of the pump driver. The pump driver stroke will depend on fluid pressure, signal current and signal frequency. The pumps may be driven at a low frequency with a continuously variable current to provide a continuously variable resolution.

The floating checks prevent fluid from rushing by during pump intake when pumping from high pressure to low pressure. This maintains the capability for high resolution.
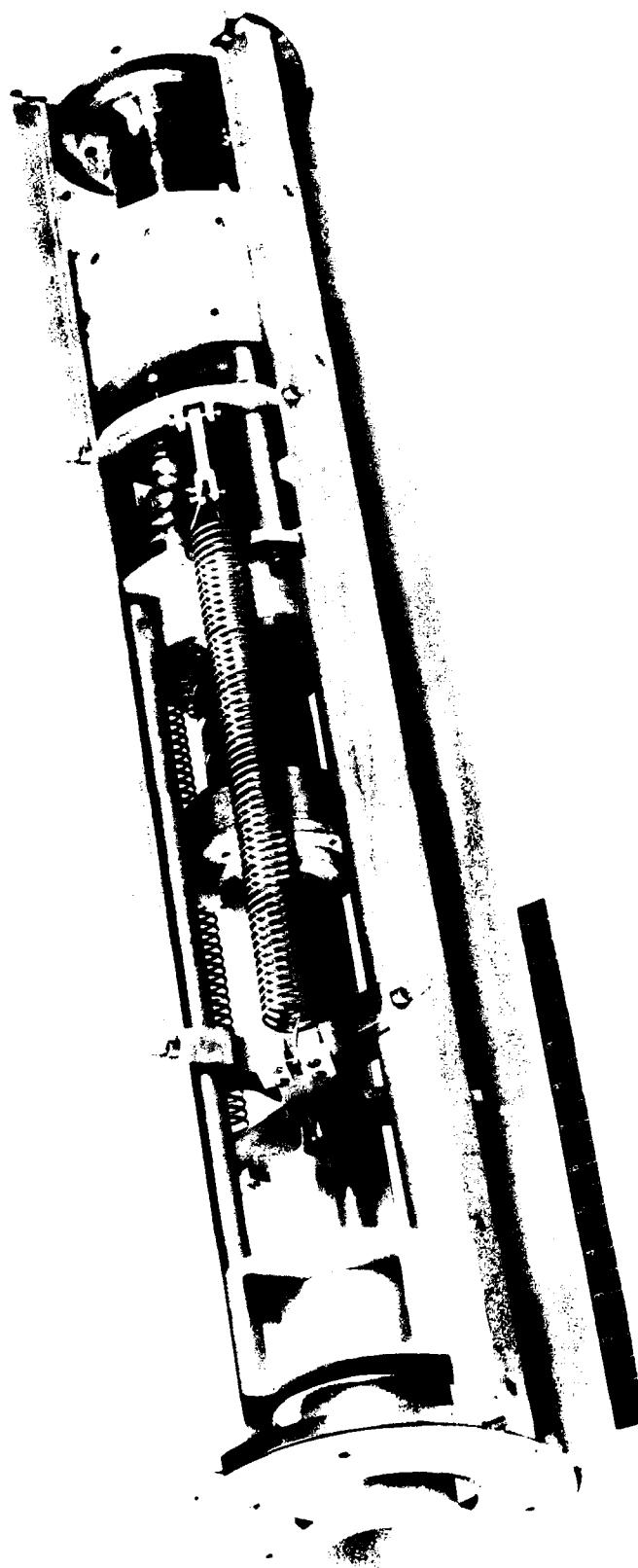
Figure 2. Linear Actuator

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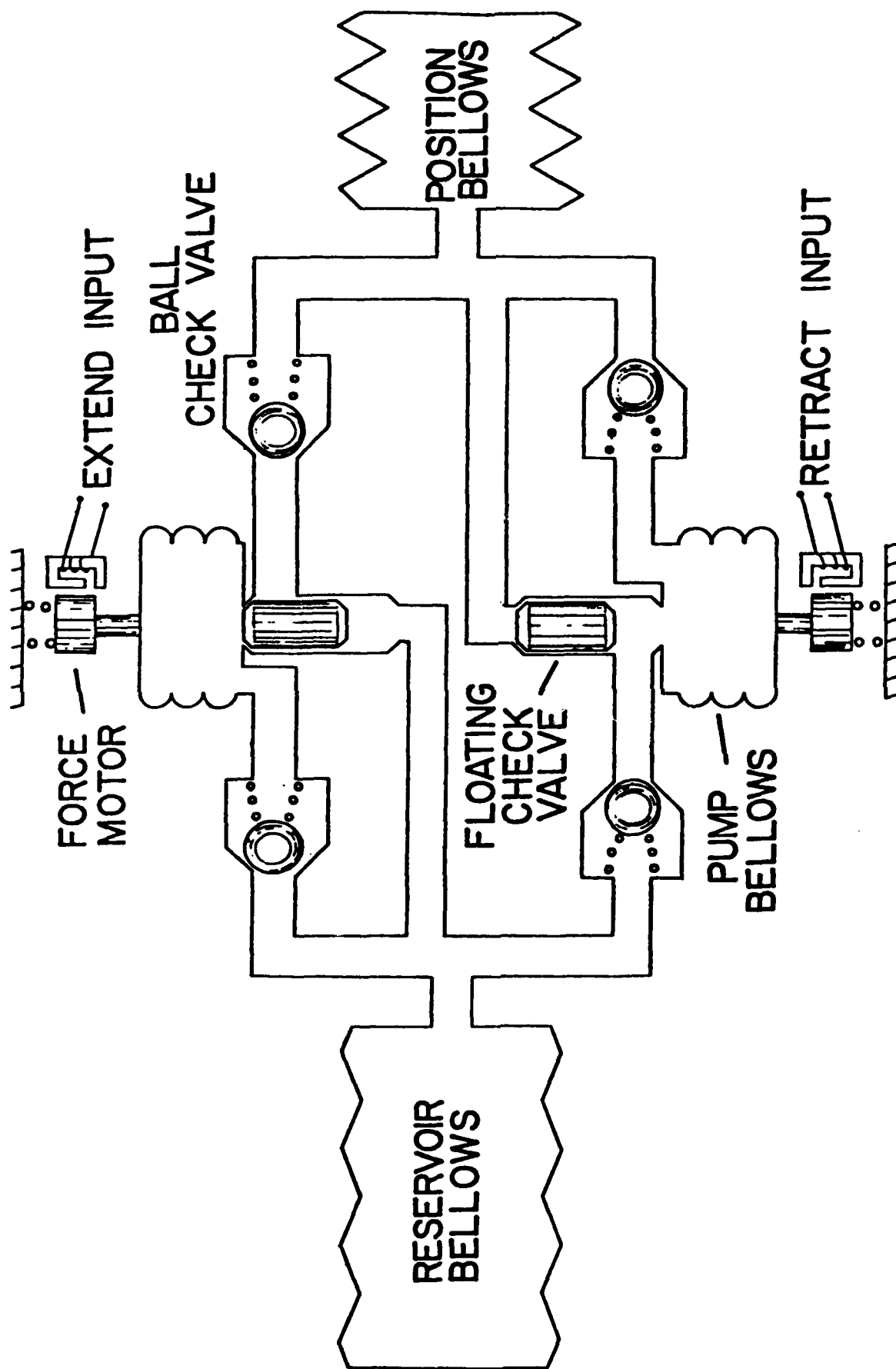
Figure 3. Fluid Schematic

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RESERVOIR BELLOWS

RETRACT PUMP BELLOWS

FLOATING CHECK

EXTEND PUMP BELLOWS

CHECK VALVE

POSITION BELLOWS
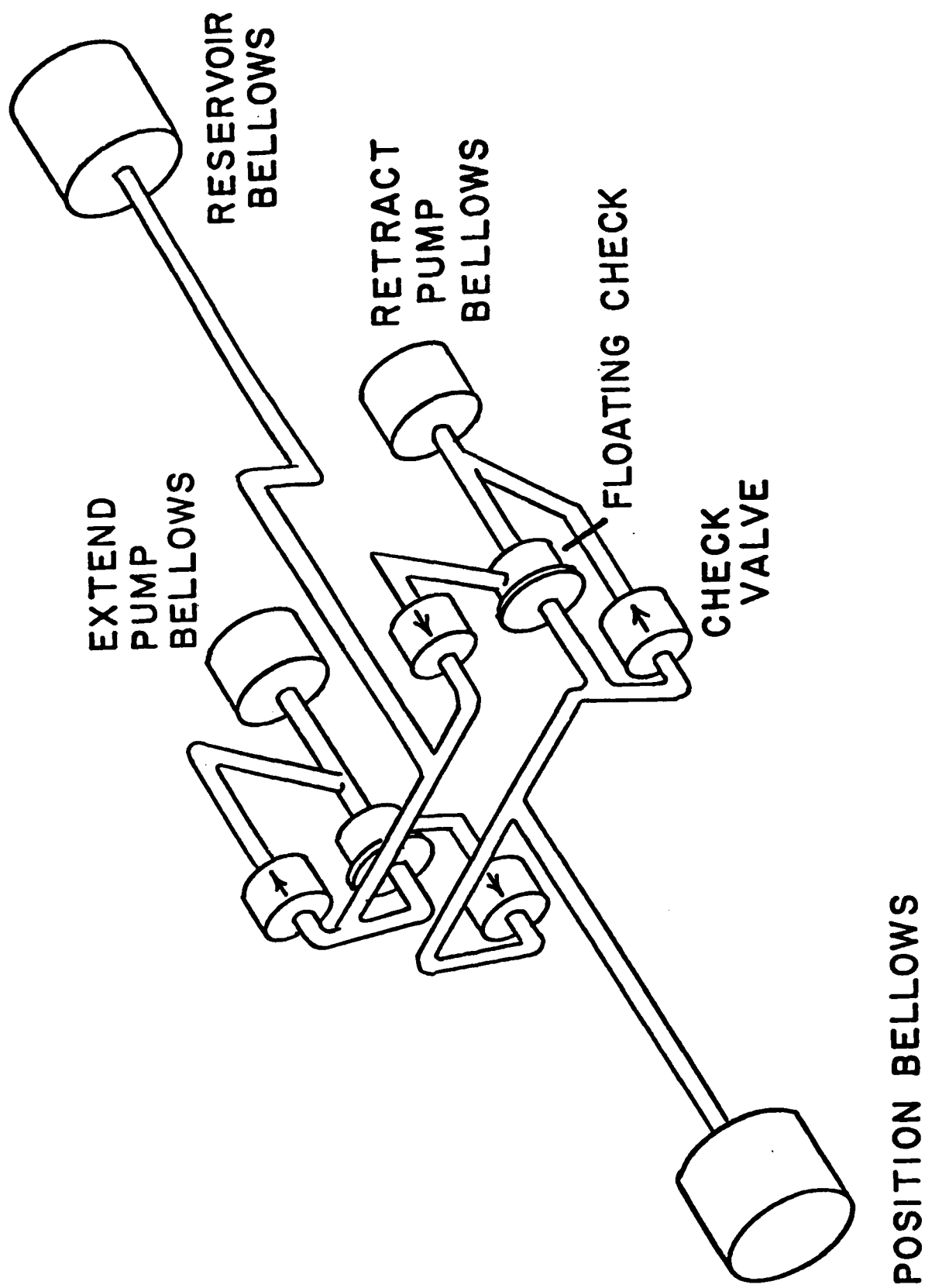
Figure 4. Fluid Circuit Pictorial

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SECTION III. HARDWARE DESCRIPTION

1. Force Motor Description

The force motors used to drive the pump bellows are a moving magnet design developed by Dynamic Controls, Inc. under Air Force contract F33615-79-C-3602. The motors develop greater than four pounds of force over a linear stroke of 0.125 inches and a force greater than three pounds over a stroke of 0.225 inches. The force is directly proportional to input current. The four pound output force is developed at a current of 1.6 amps which corresponds to an input power of 35 watts. Figure 5 is a cross section of the force motor design. The magnet material is Tascore 21 samarium cobalt, produced by Thomas & Skinner, Inc., Indianapolis, Indiana and is polarized axially.

Figure 6 shows the force motor and pump bellows hardware. Note that the magnet is located radially in the force motor with a Teflon bearing. Note also that a guide rod extends through the center of the pump bellows to provide support for the pump bellows guide rings.

Figure 7 shows the two force motors as mounted in the space actuator. The motors are connected to one end of the pump bellows. The pump bellows are constructed in three sections from 316 stainless steel. Like the position and reservoir bellows, the construction is of the edge welded type. The effective area of the pump bellows is 0.181 in.^{2}. External springs are mounted between the end of the bellows and the force motors. The springs are used to balance the force due to the quiescent pressure in the fluid circuit. A positive quiescent pressure is required for operation of the actuator in space. The check valve pumps reduce or increase the pressure in the reservoir and position bellows around the quiescent pressure.

2. Position and Reservoir Bellows Description

Figure 8 shows the position and reservoir bellows with their internal support rods. Both bellows are of edge welded construction and are made from 316 stainless steel. They have a rated effective drive area of 3.89 in.^{2}. Both bellows are fabricated in sections with a support ring between each section. The guide rods serve to guide the support rings and minimize the fluid volume inside the bellows. The support rods incorporate fill/bleed holes and are fabricated from aluminum. The end plug sections shown at the extreme left and right in Figure 8 connect the guide rod bleed holes to the fill/bleed fittings.

3. Pump Hardware Description

Figure 9 shows a poppet check valve (on the left side of the figure) and a floating check valve. The poppet check valve used is a Circle Seal cartridge with the housing modified to incorporate an "O" ring. The cartridge was designed with a cracking pressure of 0.15 psi and is fabricated primarily from aluminum. The floating check valve was designed by Dynamic Controls, Inc. and fabricated from 440C stainless steel. The poppet check is a zero leakage design incorporating a poppet with an elastomeric "O" ring. The floating check valve uses a lapped face and a lapped piston-to-bore seal.

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Figure 5. Force Motor Cross Section

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Figure 6. Force Motor and Pump Hardware

Figure 7. Force Motor Mounting

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Figure 8. Position and Reservoir Bellows

Figure 9. Check Valves

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4. Controller Description

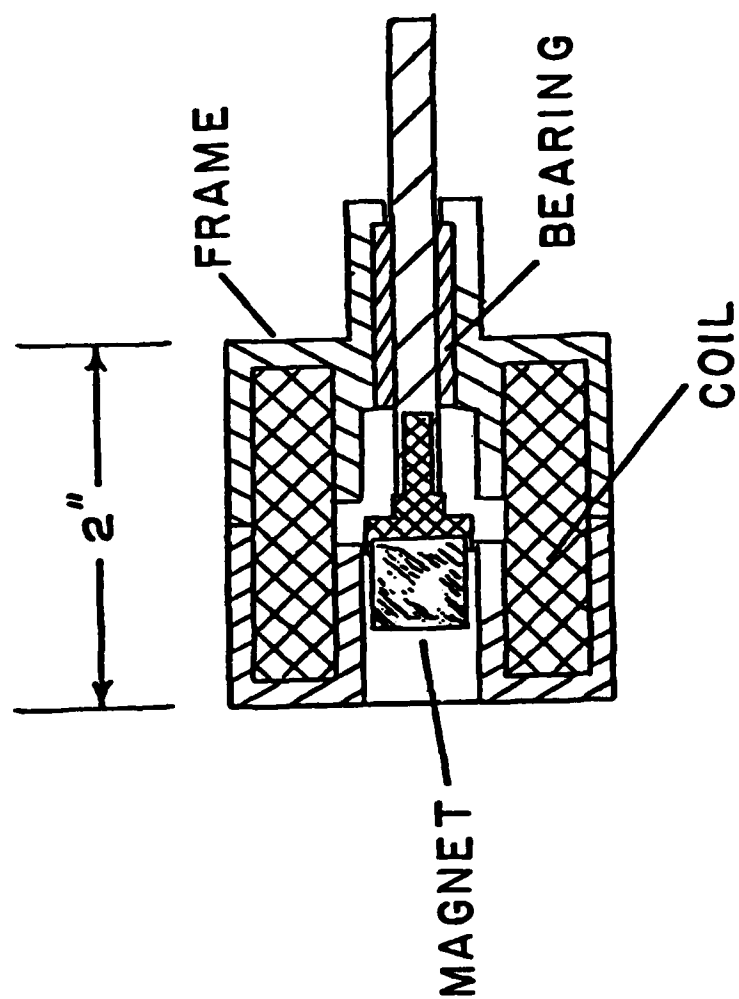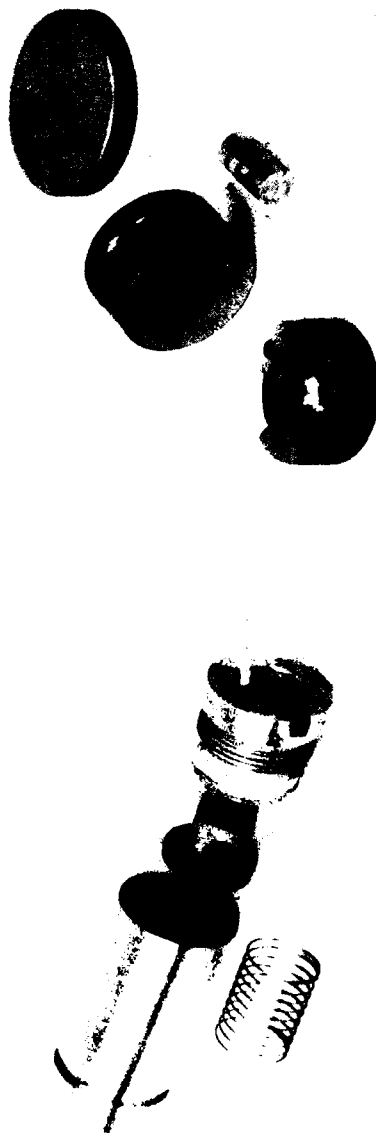Figure 10 shows the front of the controller used to drive the actuator. Front panel controls for amplitude and frequency of the output are incorporated in the design in order to investigate the effect of varying those parameters on the actuator output rate and force. A three position toggle switch is used to control the direction of the actuator's motion (which check valve pump is driven). The controller's maximum output voltage is ± 28 volts DC. The controller uses a function generator to generate a squarewave output over a frequency range of 4 to 80 Hz. A frequency counter is installed on the front panel to monitor the output frequency.

Figure 11 shows the internal construction of the controller. The output stage of the controller uses a power op amp capable of providing 2 amperes current at 28 volts to the force motors. Two 28 volt commercial power supplies are used to provide the + and − 28 volts for the power amp.

5. Actuator Support Bearings

Figure 12 shows the low friction support method allowing the extend and retract motion of the actuator. Carriage mounted Teflon rollers run in the three support rails. Two carriages are used in each rail. The rollers run on machined flat grooves in the pump body and a support ring. The grooves (and rails) are located at 120° intervals around the circumference of the actuator. The roller carriages are retained in the desired travel range by stop pins installed in the support rails.

6. Sizing Values

The actuator was designed with the following values:

a. Position and Reservoir Bellows Effective Area − 3.89 in.^{2}

b. Actuator Stroke   − 2.00 in.

c. Pump Bellows Effective Area   − 0.181 in.^{2}

d. Pump Effective Stroke   − 0.125 in.

e. Quiescent Pressure   − 14 lb./in.^{2}

f. Force Motor Coil Resistance   − 14 Ohms

g. Force Motor Driving Voltage   − 28 Volts

The selection of the quiescent pressure is arbitrary. The quiescent pressure does limit the output force of the actuator in the retract mode, since the retract pump cannot reduce the pressure in the position bellows below 0 PSIA.
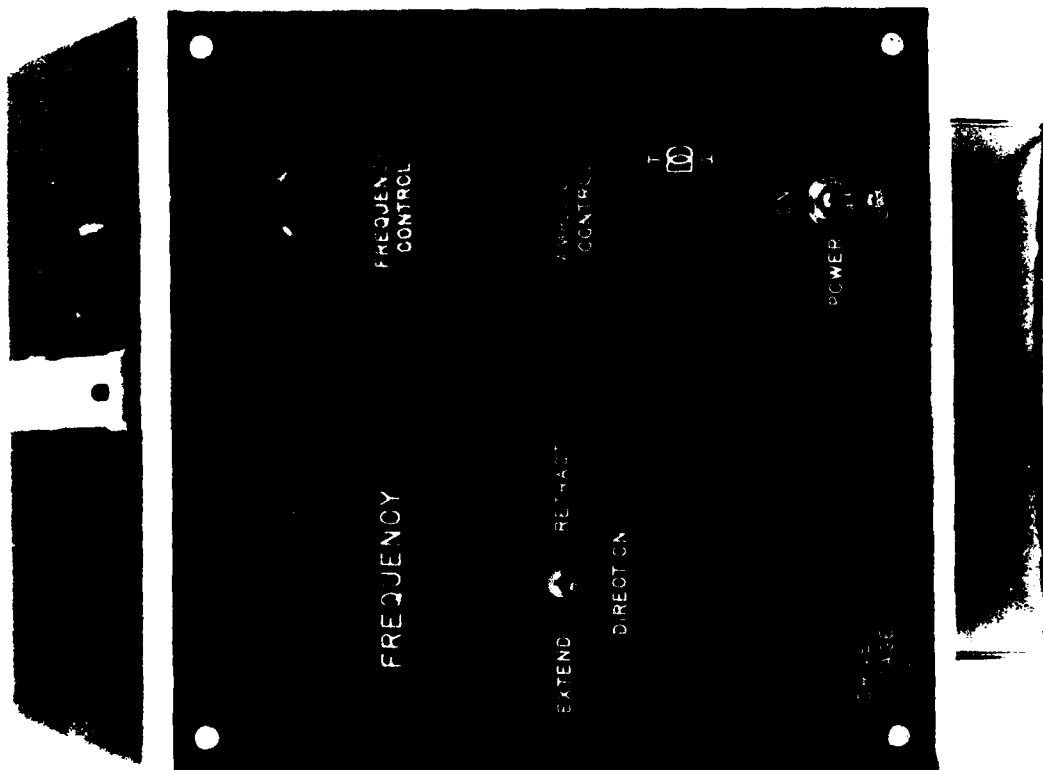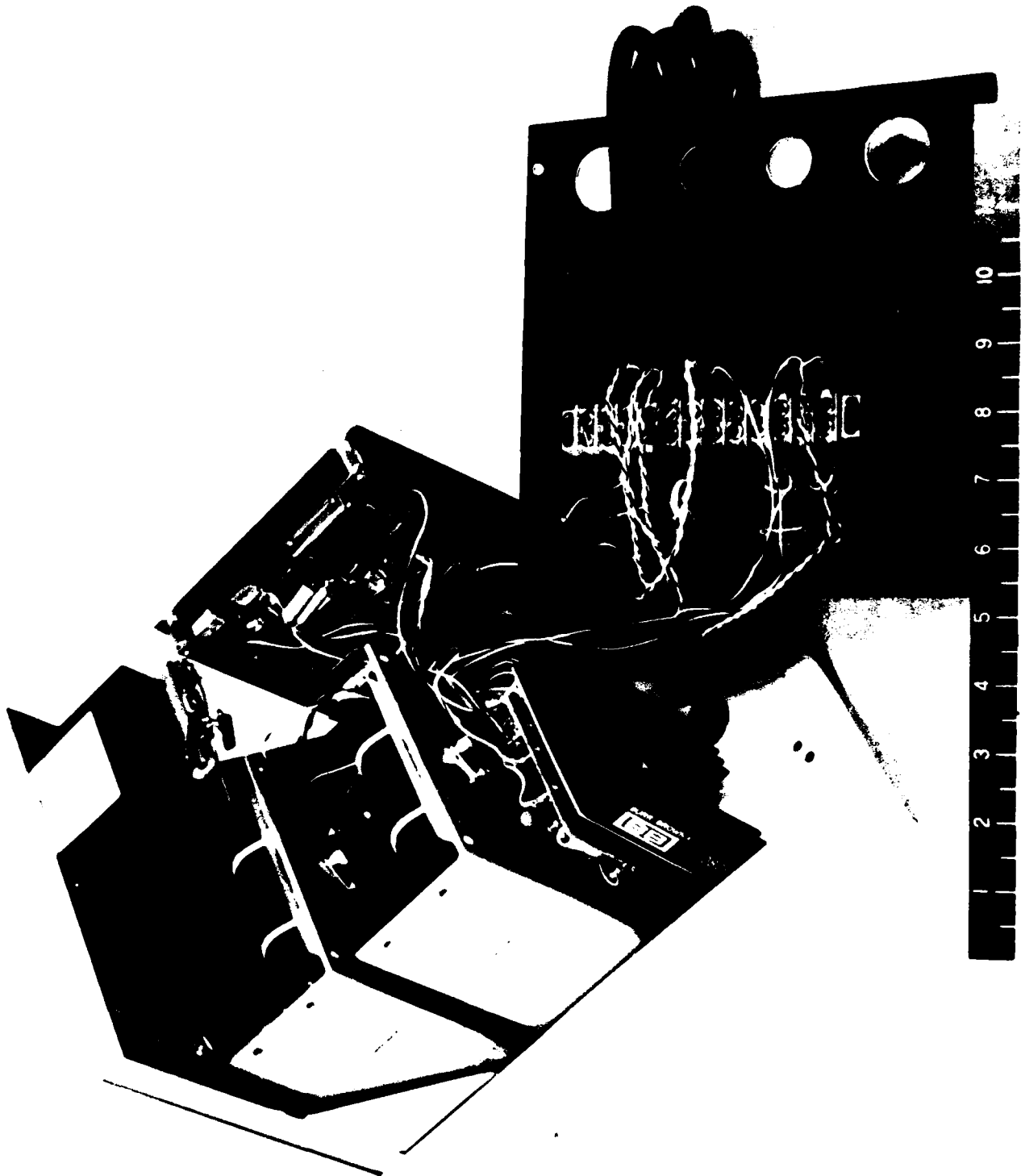
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Figure 10. Controller

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Figure 11. Controller Internal Construction

Figure 12. Roller Support

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SECTION IV. TEST RESULTS

The performance characteristics measured on the space actuator were rate of movement and force output as a function of force motor input current, frequency and position.

Figure 13 shows the extend and retract stall force characteristics as a function of the actuator position and driving current for the particular force motor. The extend force shows the expected increase with input current, since the output force for the force motors increases linearly with input current. At the center of the stroke, the maximum extend force is 37 lbs. The change in the force output at a constant input current is due to the spring rate of the position and reservoir bellows.

The retract force shown on Figure 14 shows that the maximum force output (37 pounds at center position) is independent of force motor drive current. As previously discussed, the force limitation is due to reaching an absolute pressure of zero in the position bellows. Note that this force curve is corrected for 14.7 psi ambient pressure and reflects the force generation capability of the actuator operating in the vacuum of space.

Figure 15 shows the effect of pump driving frequency upon the stall force for full extend, null and full retract positions with a current input of 1.6 amps. Note, that as the frequency of excitation for the extend pump increases above 5 Hz, the output force decreases with increasing frequency. The roll off occurs sooner than expected and reflects the particular setup adjustment on force motor used for the extend pump.

Figure 16 shows the effect of pump driving frequency upon the retract force at different positions and a constant current level of 1.6 amperes. Note that the force curve is corrected to reflect operation of the actuator in a vacuum. The output force remains constant up to a pump driving frequency of 18 Hz. The output force change with position reflects the spring rate of the position and reservoir bellows.

The maximum rate of movement at 1.6 amps peak input current at 6 Hz into the pumps was measured as:

<u>Extend Motion</u>

For full extend from retract position   0.0267 in./sec

For extend motion of 1 inch
stroke around null position   0.0294 in./sec

<u>Retract Motion</u>

For full retract from extend position   0.050 in./sec

For retract motion of 1 inch
stroke around null position   0.058 in./sec
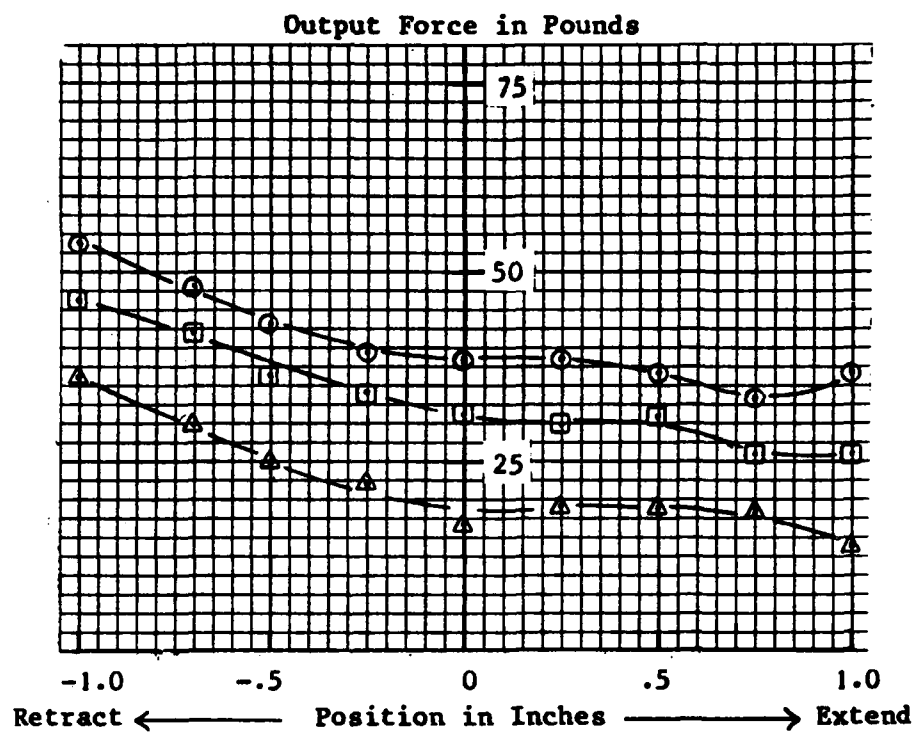
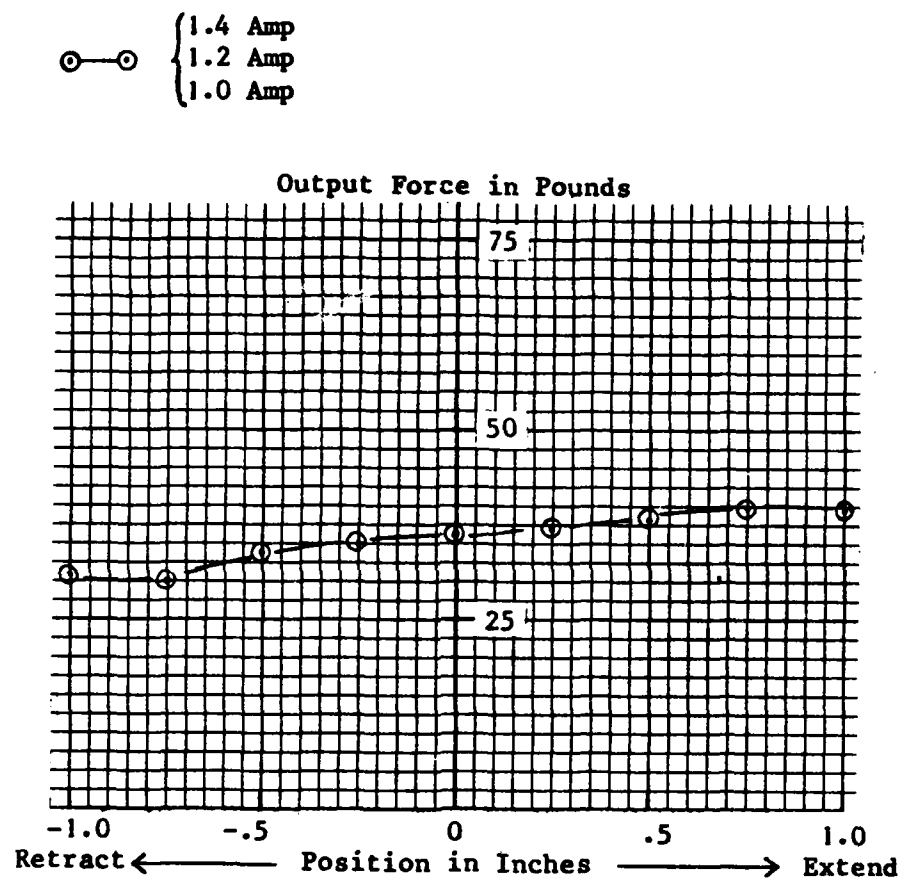Figure 13. Extend Output Force Vs Position

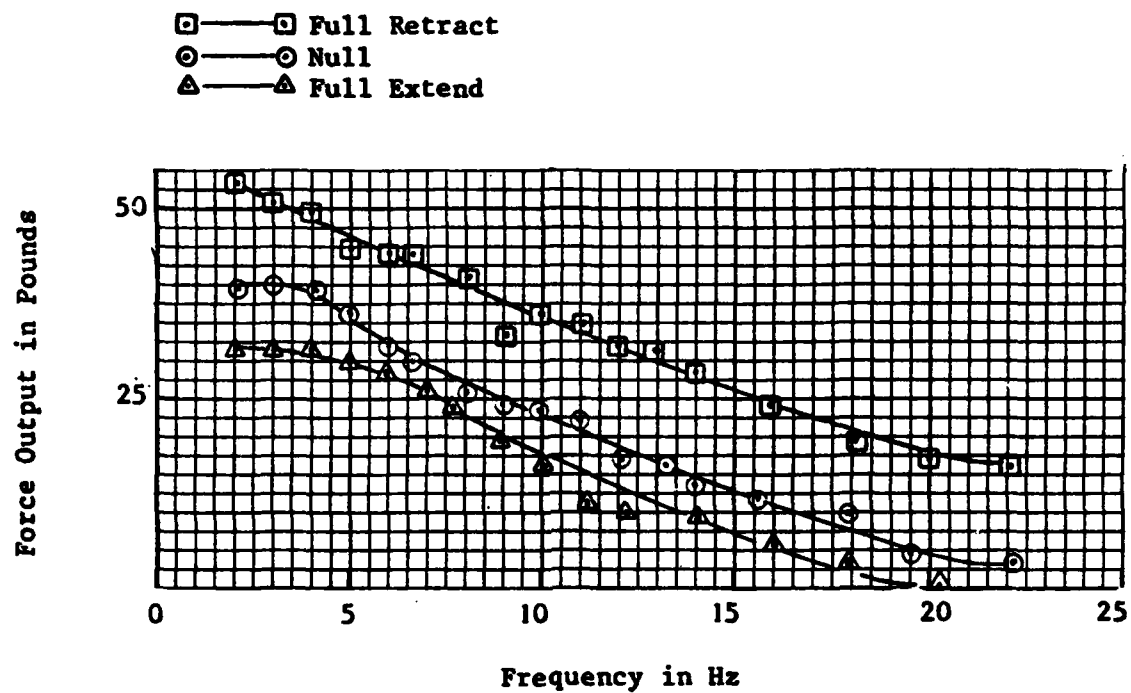Figure 14. Retract Output Force Vs Position

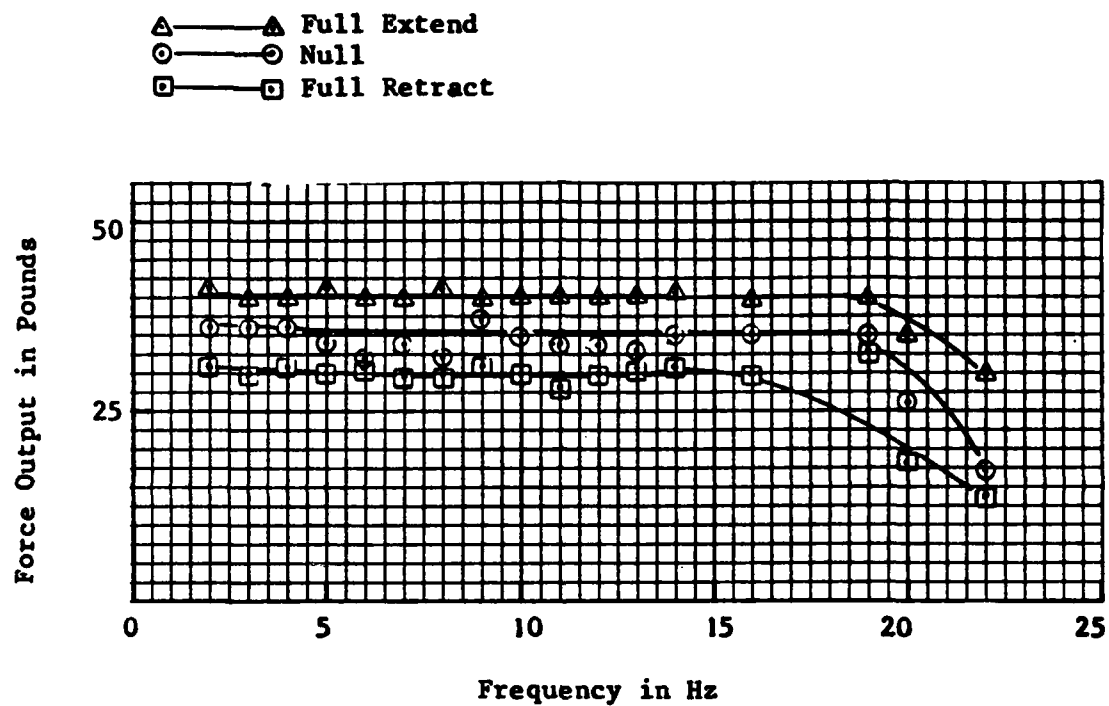Figure 15. Extend Force Output Vs Pump Frequency

Figure 16. Retract Force Output Vs Pump Frequency

The difference in the extend and retract slew rates reflects a difference between the retract and extend direction pump characteristics due to the force motor setup.

The oscillating reaction force of the pump force motors is noticeable. This could cause a vibration excitation of the structure. If this actuator were suspended in free space, it is estimated the vibration would create a motion amplitude of ± 0.01 in. at the frequency of the motor's drive signal. If the vibration level were too large, the motor design could be easily modified to push two masses in opposite directions in order to cancel the reaction force.

SECTION V. CONCLUDING COMMENTS

The hardware fabricated to demonstrate feasibility operated as expected. However, the hardware's performance has been evaluated only at room temperature. The unit is designed to operate over a wide temperature range and side to side differential temperature.

The demonstration hardware weighed 47 pounds. No attempt was made in the design to minimize size or weight. Size and weight reductions to 1/3 of the present values appear practical without performance changes.

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Handbook," Volume II, RPL-TDR-64-25, TRW Systems Group, 1968.

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